C. PROCEDURE APPLICATION (FITNET)

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- **INTRODUCTION**
- **INPUTS**
- **ASSESSMENT ROUTES**
- **SPECIAL OPTIONS**

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INTRODUCTION

INTRODUCTION

The FITNET fatigue module provides a series of assessment procedures or routes for evaluating the effect of cyclic or fluctuating loads. Two basic scenarios are foreseen:

a) There is no pre-existing flaw or defect, and the goal of the analysis is to determine the accumulation of fatigue damage at a critical location (fatigue damage analysis). In this case the basic approach is to determine the fluctuating stress range at the location in question and to relate this to appropriate fatigue life curves. Three different routes are proposed (Routes 1, 2 and 3), depending on the complexity of the loading.

b) A real or postulated defect or flaw is present, and the goal of the analysis is to determine the growth of that flaw to a certain critical size. Two different routes are considered: The case of planar flaw in Route 4 and the case of non planar defects in Route 5.

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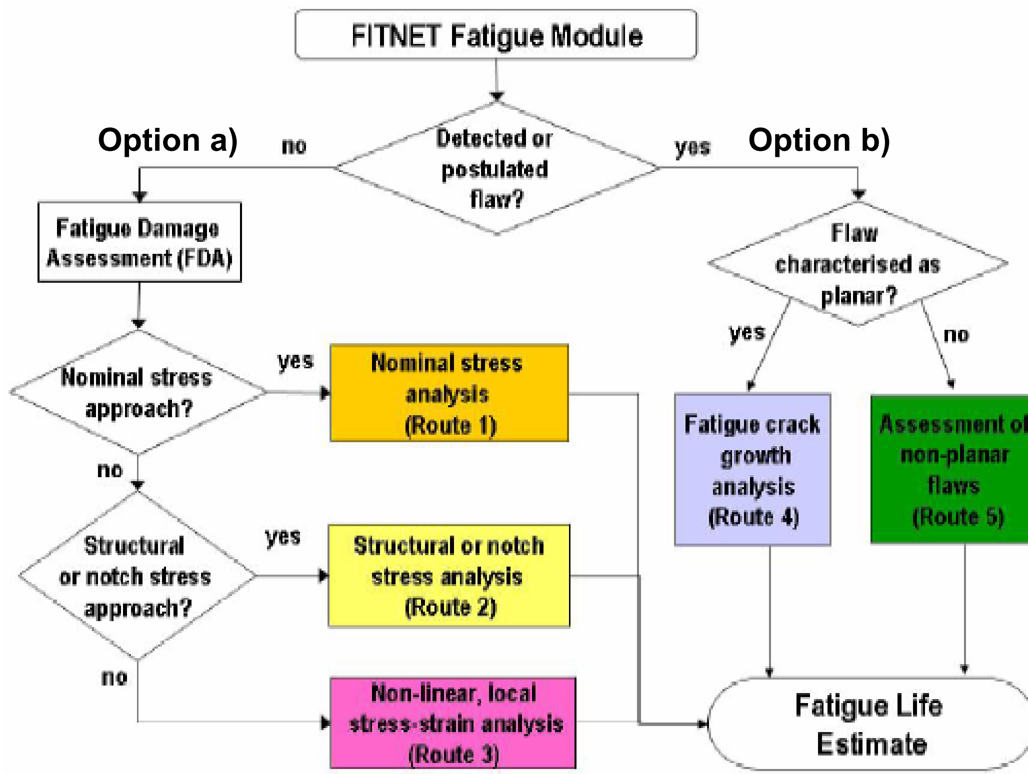
Both option a) and b) can be applied to either welded or non-welded structures. The overall scheme is shown in the figure.



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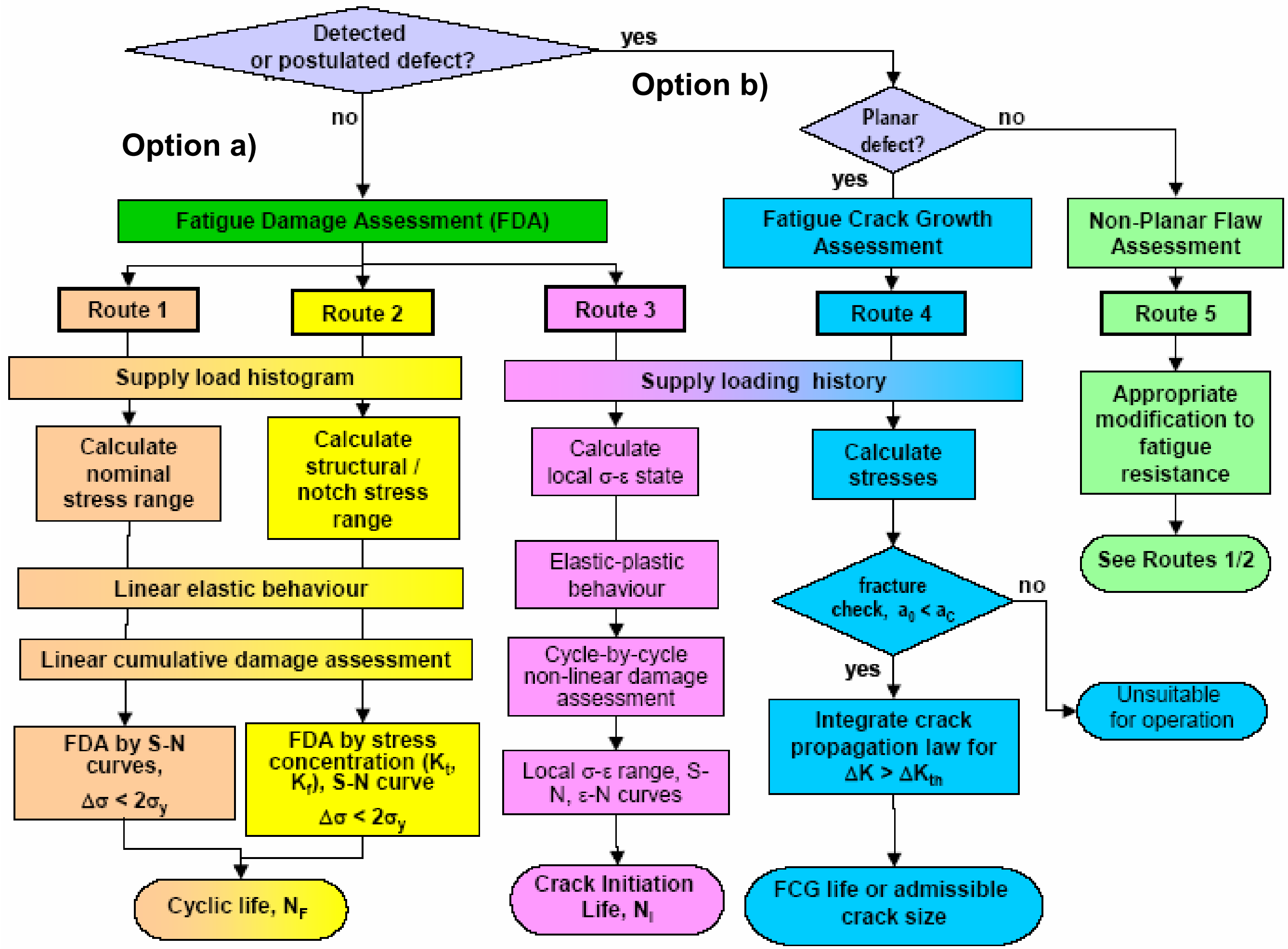
The scope and background to the five assessment routes are briefly described in the following, while this figure shows the basic steps used in applying these.



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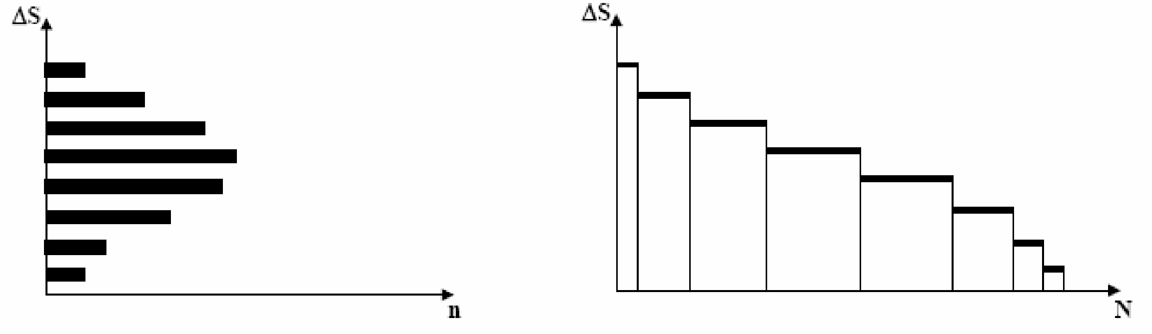
INPUTS

INPUTS: Description of variable loads

To assess fatigue risk it must be known the stress variation versus time.

In practice, the more commonly applied methods in design allow the use of the stress range distribution (histogram) versus the number of cycles.



a) stress range distribution

b) stress range cumulative distribution

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INPUTS

INPUTS: Partial Safety Factors

Depending on the level of safety built into the fatigue resistance data being used in the assessment, the confidence with which the fatigue actions can be estimated and possibly the consequences of fatigue failure, partial safety factors may need to be introduced. Those applied to the fatigue actions are termed γ_F while those applied to the resistance data are termed γ_M .

INPUTS: Fatigue Actions

Fatigue assessments are carried out using the design spectrum (histogram) of the fatigue actions in terms of stress ranges $\Delta\sigma_{i,s,d}$, which correspond to the stresses of the characteristic spectrum (histogram) $\Delta\sigma_{i,s,k}$ multiplied by the partial safety factor γ_F for fatigue actions.

For constant amplitude loading, the characteristic and design spectra are reduced to only one stress level, $\Delta\sigma_{s,d}=\Delta\sigma_{s,k}\cdot\gamma_F$

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INPUTS

INPUTS: Cumulative Fatigue Assessment

A cumulative fatigue assessment is applied in situations where it is considered that fatigue crack initiation and growth can be tolerated without the risk of failure during the required lifetime. The fatigue resistance is usually derived from constant or variable amplitude tests. The fatigue resistance data given in the Procedure are based on published results from constant amplitude tests.

The fatigue resistance data must be expressed in terms of the same stress (Nominal, Hot spot, Notch) or strain as that controlled or determined during the generation of those data.

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INPUTS: Cumulative Fatigue Assessment (cont.)

The fatigue resistance data are based on the number of cycles N to failure. The data are represented in S-N curves (see Section 5).

$$N = \frac{C}{\Delta\sigma^m} \quad \text{or} \quad N = \frac{C}{\Delta\tau^m}$$

where:

$\Delta\sigma$	normal stress range
$\Delta\tau$	shear stress range
N	number of cycles to failure
C, m	material and assessed detail constants

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INPUTS

INPUTS: Cumulative Fatigue Assessment (cont.)

The fatigue resistance is defined by the mean curve (50% probability of survival) and the Log (C) standard deviation.

The conventional fatigue resistance data can be given as characteristic values, $\Delta\sigma_{R,k}$ or $\Delta\tau_{R,k}$, which are assumed to have a survival probability of at least 95%, calculated from a mean value of a two-sided 75% confidence level.

In practice these characteristic values may be reduced further by dividing them by a partial safety factor γ_M to give the design resistance values, $\Delta\sigma_{R,d}$ and , $\Delta\tau_{R,d}$ used in the fatigue assessment. The design resistance S-N curve may be modified further according to the needs of the damage calculation procedure.

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INPUTS

INPUTS: Cumulative Fatigue Assessment (cont.)

For constant amplitude loading, the characteristic stress range , $\Delta\sigma_{R,k}$ at the required number of stress cycles is firstly determined. Secondly, the fatigue design criterion is checked:

$$\Delta\sigma_{s,d} = \Delta\sigma_{s,k}\gamma_F < \Delta\sigma_{R,d} = \frac{\Delta\sigma_{R,k}}{\gamma_M}$$

For variable amplitude loading, the fatigue damage due to the applied load spectrum is assessed using a linear cumulative damage summation rule. Thus in a fatigue damage assessment has to be shown that:

$$\sum \frac{n_i}{N_i} < D$$

D : specified allowable damage sum

i Index for block number in load spectrum of required design life

n_i number of cycles of design load stress range $\Delta\sigma_{i,s,d}$ in load spectrum block i

N_i: number of cycles at which design stress range $\Delta\sigma_{i,s,d}$ causes failure in modified design fatigue resistance S-N curve.

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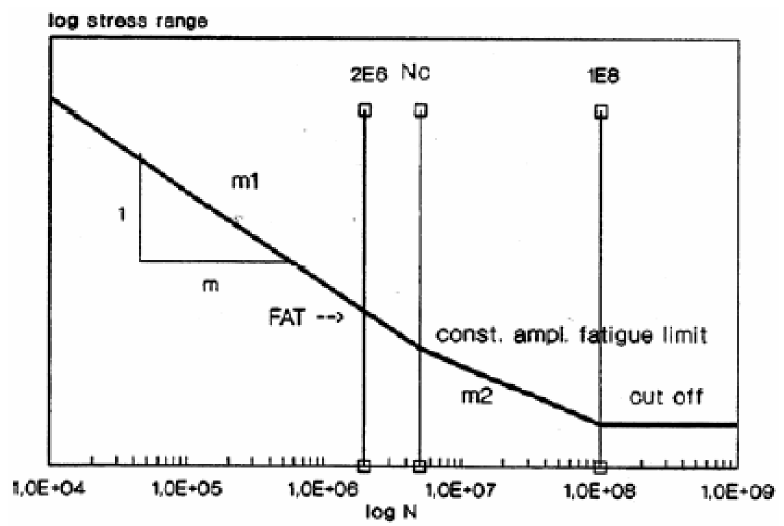
INPUTS

INPUTS: Cumulative Fatigue Assessment (cont.)

The order of the sequence of the blocks has no effect on the results of this calculation. Note that it will rarely be valid to assume that applied stresses lower than the constant amplitude fatigue limits are non-damaging. In practice the fatigue damage induced by higher stresses in the spectrum will have the effect of gradually lowering the effective fatigue limit. As a result, stresses below the original fatigue limit become increasingly damaging as the fatigue life progresses. To allow for this it is common to assume that the design S-N curve from which i values are obtained the form shown in the figure.



Generic S-N curve for welded joints used in cumulative damage calculations

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INPUTS

INPUTS: Fatigue Limit Assessment

A fatigue limit assessment is one that is applied to cases where no significant fatigue crack growth can be tolerated, for example because there is a risk of failure from a small crack or a very high number of stress cycles, typically greater than 10^9 cycles, are to be endured.

The fatigue limit resistance is defined by the stress range, $\Delta\sigma_{L,R}$, below which the lifetime is considered to be infinite from an engineering point of view. Again, characteristic values ,$\Delta\sigma_{L,R,k}$, are reduced to design values $\Delta\sigma_{L,R,d}=\Delta\sigma_{L,R,k}/\gamma_M$.

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INPUTS

INPUTS: Fatigue Limit Assessment (cont.)

When the fatigue limit assessment is applied for constant amplitude loading, the design verification criterion is:

$$\Delta\sigma_{M,s,d} < \Delta\sigma_{L,R,d}$$

where $\Delta\sigma_{M,s,d}$ is the maximum applied stress range and $\Delta\sigma_{L,R,d}$ is the design acceptable fatigue limit stress range.

For variable amplitude loading, if the maximum design stress range $\Delta\sigma_{M,s,d}$ of the load spectrum is lower than the design fatigue limit $\Delta\sigma_{L,R,d}$ of the design fatigue resistance S-N curve, or if it is lower than the design cut-off limit $\Delta\sigma_{cut,R,d}$ in cases where no fatigue limit is given, the life of the assessed detail can be assumed to be infinite and no further damage calculation is necessary.

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INPUTS

INPUTS: Environmental Issues

The fatigue resistance data given here refer to non-corrosive environments (air) and for structures with normal protection against atmospheric corrosion. For free atmospheric corrosion, in particular sea environment, the SN curve to be applied can be derived from the standard curve applying the following conditions:

- the curve has no fatigue limit nor cut-off and no change of slope
- the life time is divided by 2

Concerning service temperature, unless stated otherwise the fatigue resistance data refer to temperatures lower than 100°C; a fatigue reduction factor has to be considered beyond this temperature level.

If the effect of environment cannot be excluded, then the assessment should be made using the creep or corrosion modules (see sections 8 and 9 respectively).

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INPUTS

INPUTS: Exemption for Fatigue Assessment

The Procedure provides criteria to determine when fatigue assessment is not required (see Section 7.2.3)

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FATIGUE ASSESSMENT ROUTES

ROUTE 1 – Fatigue Damage Assessment Using Nominal Stresses

This route considers **nominal elastic stress** values for the location of interest and the fatigue life N_f is determined from a **set of S-N curves** classified according to different classes or levels of fatigue resistance i.e. the effects of local geometric, weld or microstructural details and, if relevant, residual stress are accounted for in the S-N curve itself.

It is based on currently used procedures (e.g. IIW guidelines for welded joints).

The linear cumulative damage law is used to deal with variable load spectra is **based on Miner rules**.

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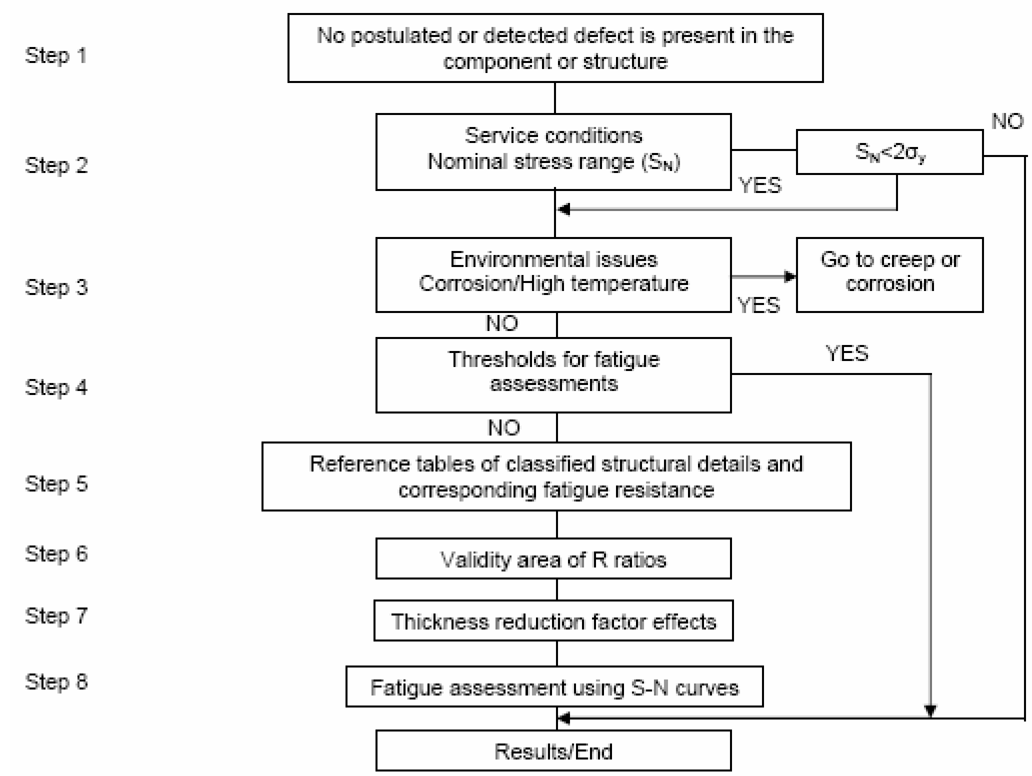
ASSESSMENT ROUTES

ROUTE 1- Fatigue Damage Assessment Using Nominal Stresses

WELDED COMPONENTS



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ASSESSMENT ROUTES

ROUTE 1- Fatigue Damage Assessment Using Nominal Stresses

WELDED COMPONENTS

Step 1 No postulated or detected defect is present in the structure

The route 1 assumed that no defect is postulated or is detected by NDE in the structure or component which is assessed in fatigue. Annexe D in the Procedure is providing guideline on NDE detection.

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ASSESSMENT ROUTES

ROUTE 1- Fatigue Damage Assessment Using Nominal Stresses

Step 2 Service condition

Nominal stress range SN. Guide on this is given in the Procedure (see Section 7.3)

Step 3 Environmental issues (see 7.2.2)

Step 4 Thresholds for fatigue assessment (see 7.2.3)

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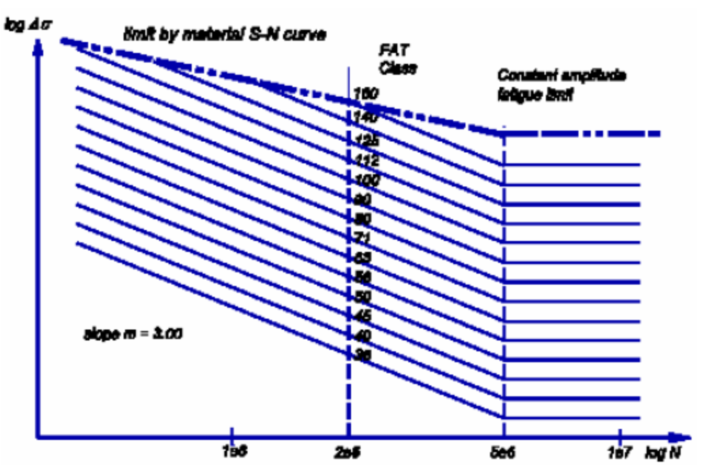
ASSESSMENT ROUTES

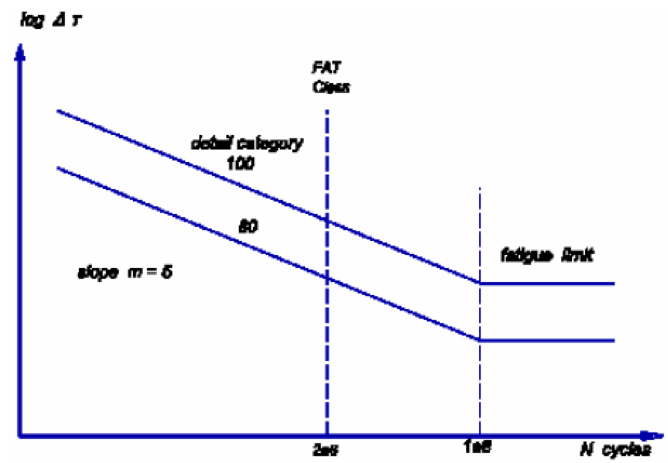
ROUTE 1- Fatigue Damage Assessment Using Nominal Stresses

Step 5 Fatigue Resistance Data Specification

Separate S-N curves are provided for consideration of normal and shear stresses:



Fatigue resistance S-N curves for m=3, normal stress (steel)



Fatigue resistance S-N curves for shear stress (steel)

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ASSESSMENT ROUTES

ROUTE 1- Fatigue Damage Assessment Using Nominal Stresses

Step 6 Validity area of R ratios

For stress ratios R<0.5 a fatigue enhancement factor f(R) may be considered by multiplying the fatigue class of classified details by f(R). Values of f(R) are given in the Procedure (see Section 7.3.1.1.6).

Step 7 Thickness reduction factor effects

The influence of the plate thickness on fatigue strength should be taken into account in cases where cracks start from the weld toe on plates thicker than 25 mm and lower than 5 mm (see Section 7.3.1.1.7)

Step 8 Fatigue assessment using S-N Curves (see 7.3.1.1.8)

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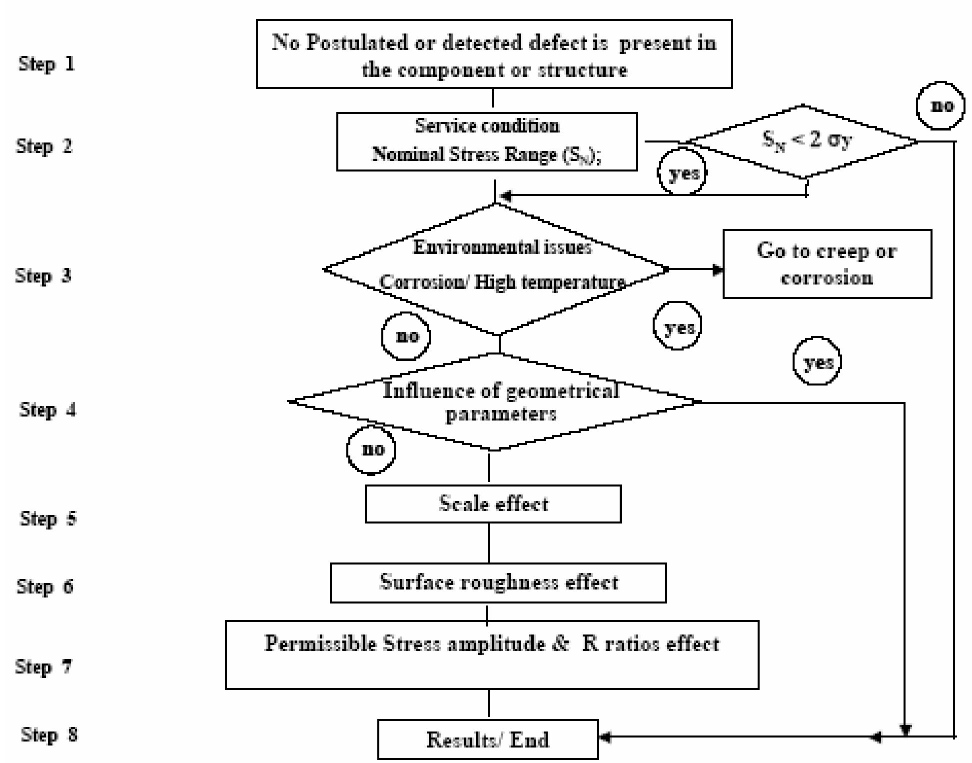
ASSESSMENT ROUTES

ROUTE 1- Fatigue Damage Assessment Using Nominal Stresses

NON-WELDED COMPONENTS



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ASSESSMENT ROUTES

ROUTE 1- Fatigue Damage Assessment Using Nominal Stresses

The conventional approach starts from the knowledge of the fatigue resistance of the base material submitted to fatigue cycles.

This approach leads to modify this « intrinsic » endurance or reliability limit, σ_D, by taking into account of influencing parameters such as :

- the geometrical discontinuities of the components (notch effect, Step 4, see 7.3.1.2.4.1)
- its size (step 5, scale effect, see 7.3.1.2.4.2)
- the surface roughness (step 6, surface effect, see 7.3.1.2.4.3)
- the mean stress σ_m (step 7, mean stress effect, see 7.3.1.2.5)

Finally, the permissible nominal stress σ_a , is derived and compared to the actual (nominal) stress, σ_e applied to the component.

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FATIGUE ASSESSMENT ROUTES

ROUTE 2 – Fatigue damage assessment using structural or notch stresses

This route considers that the appropriate structural stress in a critical area of a component could be calculated by FEA or by formula. In some case it could also be measured by following specific methods. Two approaches are possible:

a)calculate the structural stress and apply with appropriate class S-N curves

b)calculate a notch stress via stress concentration factors such as K_t or K_f. and apply with appropriate S-N curves

The Palmgren-Miner linear cumulative damage rule is used to deal with variable loads.

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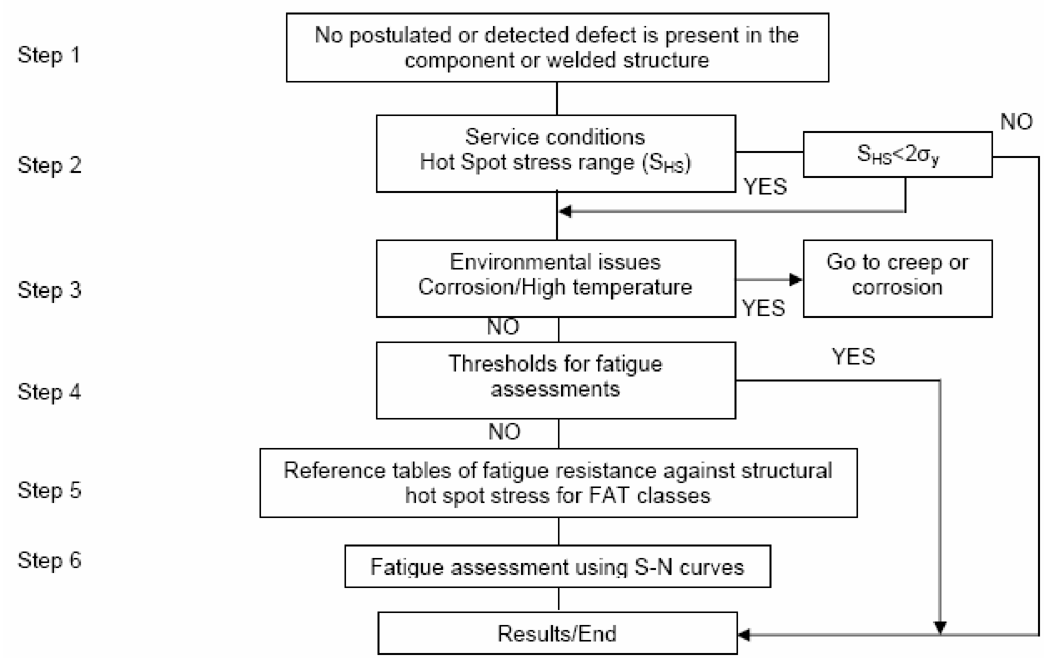
ASSESSMENT ROUTES

ROUTE 2- Fatigue Damage Assessment Using Structural or Notch Stresses

WELD COMPONENTS



Stepwise flowchart for Route 2. Weld components.

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ASSESSMENT ROUTES

ROUTE 2- Fatigue Damage Assessment Using Structural or Notch Stresses

WELD COMPONENTS

Step 1: No postulated or detected flaw is present in the structure

The route 2 assumed that no defect is postulated or is detected by NDE in the structure or component which is assessed in fatigue. The fatigue assessment is based on fatigue linear damage analysis. FITNET procedure provides guideline on NDE detection (see Annex D).

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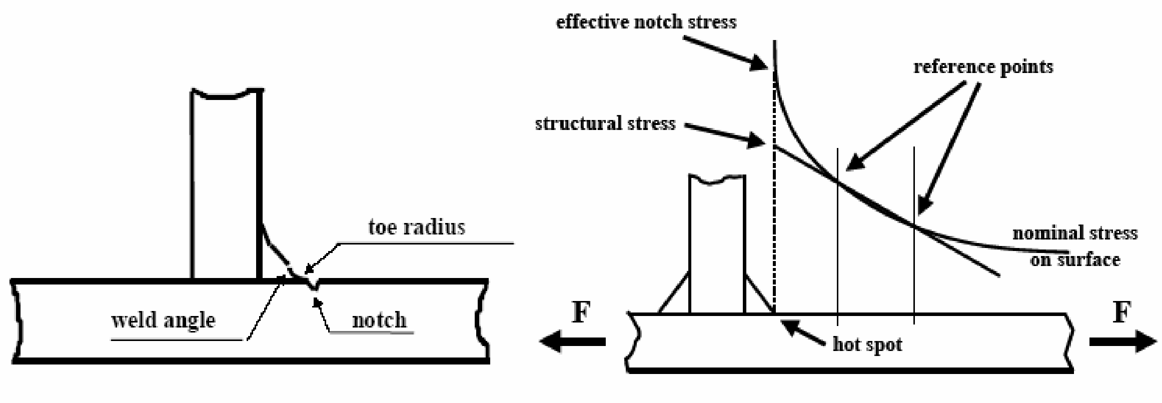
ASSESSMENT ROUTES

ROUTE 2- Fatigue Damage Assessment Using Structural or Notch Stresses

Step 2: Service condition

Fatigue resistance will be calculated in route 2 by using Hot spot stress range S_{HS} or Notch Stress range ($\Delta\sigma_{notch}$) calculation.

The structural hot spot stress and effective notch stress are defined versus the nominal stress by means of two stress coefficient factors: structural hot spot stress SCF_{HS} and notch effect SCF_{NS}. The procedure provides guidance for the calculation of these coefficients in 7.3.2.1.2.



Hot spot and notch stress in a welded joint.

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ASSESSMENT ROUTES

ROUTE 2- Fatigue Damage Assessment Using Structural or Notch Stresses

Step 3 Environmental issues (see Section 7.2.2)

Step 4 Thresholds for fatigue assessment (see Section 7.2.3)

Step 5 Fatigue Data Specifications (see Section 7.3.2.1.5)

Step 6 Fatigue assessment using S-N Curves (see 7.3.2.1.6)

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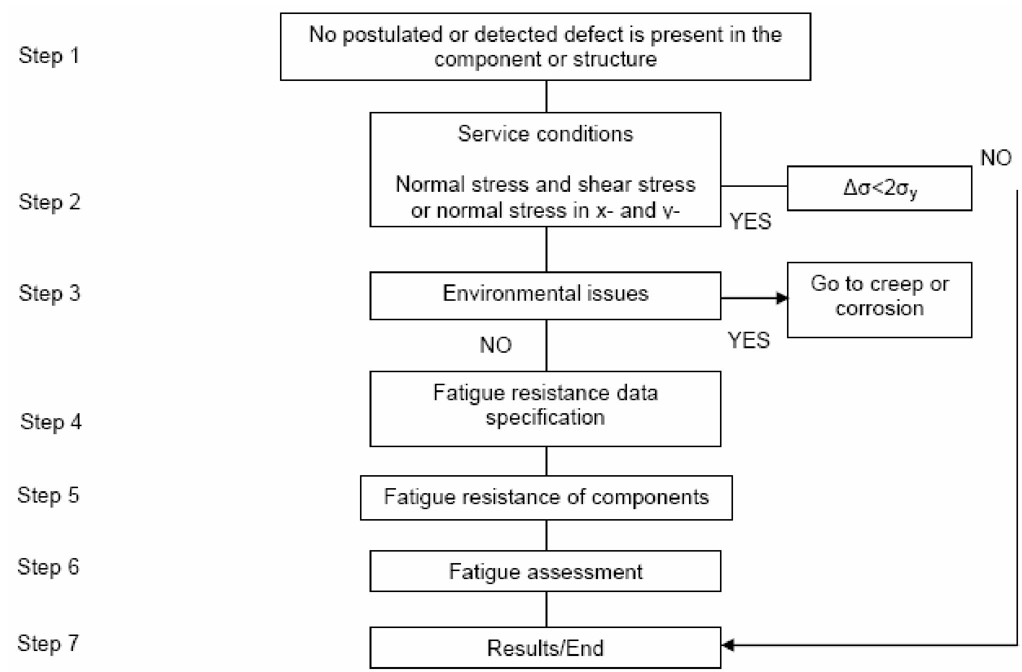
ASSESSMENT ROUTES

ROUTE 2- Fatigue Damage Assessment Using Structural or Notch Stresses

NON-WELDED COMPONENTS



Stepwise flowchart for Route 2. Non-welded components.

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ASSESSMENT ROUTES

ROUTE 2- Fatigue Damage Assessment Using Structural or Notch Stresses

NON-WELDED COMPONENTS

Step 1: No Postulated or detected defect is present in the component or structure

The Route 2 assumes that no detect is postulated or is detected by NDE in the component which is assessed in fatigue.

Step 2: Service condition

FITNET FFS provides guidance for the definition of Service Condition in non-welded components (see 7.3.2.2.2).

Step 3 Environmental issues, corrosion and high temperatures.

The procedure provides temperature limits for applying the fatigue module (see Section 7.3.2.2.3).

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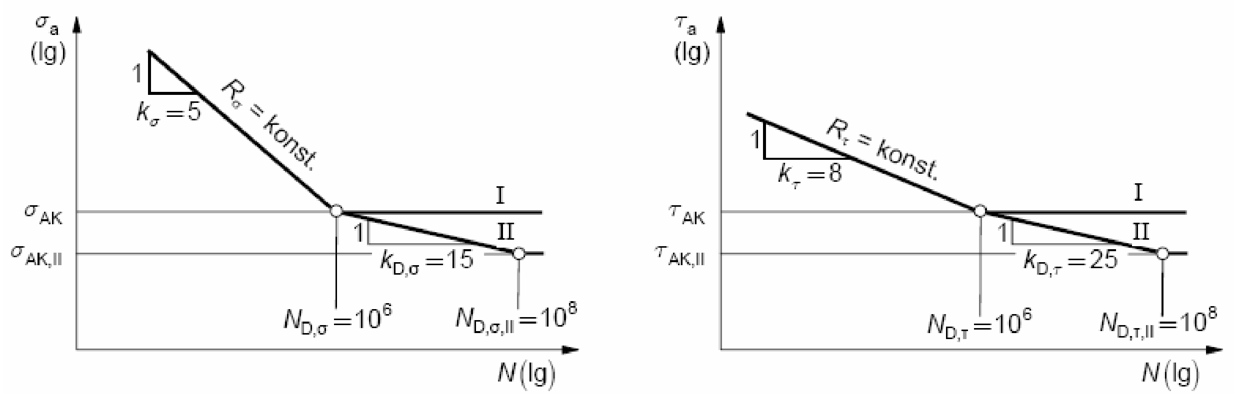
ASSESSMENT ROUTES

ROUTE 2- Fatigue Damage Assessment Using Structural or Notch Stresses

Step 4 Thresholds for fatigue assessment (see Section 7.2.3)
Step 5: Fatigue resistance data specification

The constant amplitude resistance curves in terms of amplitudes of local elastic stresses, σ_a, are given as specified in the figure (see 7.3.2.2.5)



Step 6: Fatigue Assessment (see Section 7.3.2.2.6)

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FATIGUE ASSESSMENT ROUTES

ROUTE 3 - Fatigue damage assessment using local stress-strain approach stresses

This route is mainly directed at non-welded applications and foresees direct calculation of strains at a critical location using an appropriate elastic or elasto-plastic description of the material behaviour.

The fatigue life is then determined from a strain range vs. cycles to initiation curve or relation such as the Manson-Coffin law.

It is also noted that the analysis can be taken further by considering subsequent crack growth using fracture mechanics (route 4).

The summation of life consumption is performed cycle-by-cycle, allowing for non-linear damage accumulation effects if necessary.

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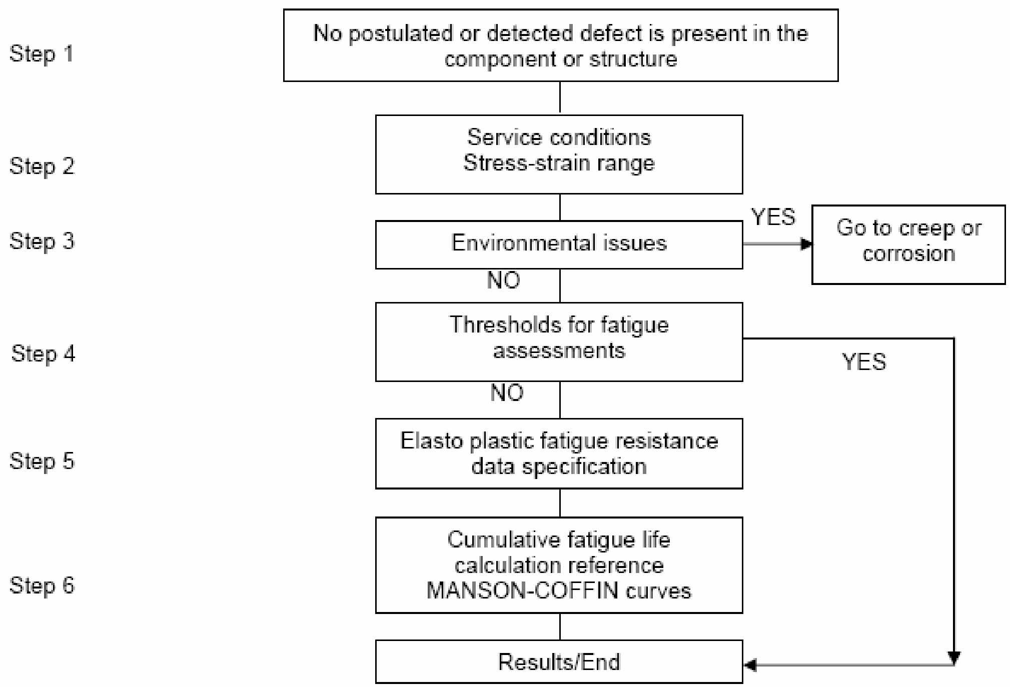
ASSESSMENT ROUTES

ROUTE 3 - Fatigue damage assessment using local stress-strain approach stresses



Stepwise flowchart for Route 3

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ASSESSMENT ROUTES

ROUTE 3 - Fatigue damage assessment using local stress-strain approach stresses

Step 1 No postulated or no detected defect is present in the component or structure

The route 3 assumes that no defect is postulated or is detected by NDE in the structure or component which is assessed in fatigue.

Step 2 - Service Condition

The approach concerns the fatigue life assessment of a component with a high local stress concentration such as a groove or a notch, where the local surface roughness at the bottom of such features cannot be measured. For medium local stress concentrations such as shaft shoulders and grooves with medium to large radii (for which the local surface roughness can be measured) Route 1 can be applied. These analyses can be performed cycle-by-cycle, allowing for non-linear damage accumulation effects if necessary. For further details, see 7.3.3.2.

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ASSESSMENT ROUTES

ROUTE 3 - Fatigue damage assessment using local stress-strain approach stresses

Step 3 Environmental issues (see 7.2.2)

Step 4 Thresholds for fatigue assessment (see 7.2.3)

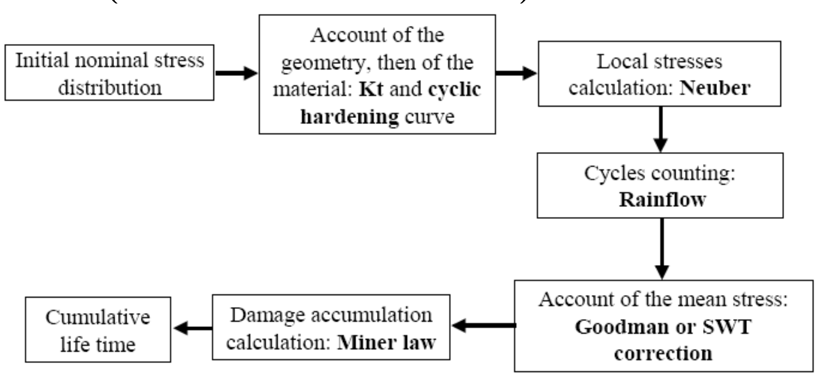
Step 5 Fatigue resistance data for elasto-plastic loading

- Material elastoplastic behaviour, Neuber-rule (see Section 7.3.3.5.1)

Step 6 Cumulative Fatigue life calculation

The Procedure provides guidance for this purpose.

The figure provides a scheme of such calculations.



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FATIGUE ASSESSMENT ROUTES

ROUTE 4 – Fatigue crack growth assessment

This route addresses the assessment of detected or postulated planar flaws that can be considered as macrocracks. The initial flaw position, size and orientation can be determined in two ways: either based on the reported or detected size from non-destructive inspection results or from a postulated flaw, based on consideration of service experience, the manufacturing process, resolution limits of a non destructive technique, from the threshold stress intensity factor etc.

The basic approach foreseen for calculating fatigue crack growth is via the standard Paris law. A more sophisticated approach is also provided, based on the Forman-Mettu equation (see Reference 7.4 in the Procedure).

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ASSESSMENT ROUTES

ROUTE 4 – Fatigue crack growth assessment

The procedure is based on a **fracture mechanics analysis**, which assumes that a **flaw may be idealized as a sharp tipped crack** which **propagates in accordance with the law relating the crack growth rate**, da/dN, **and the range of stress intensity factor**, ΔK, for the material containing the flaw.

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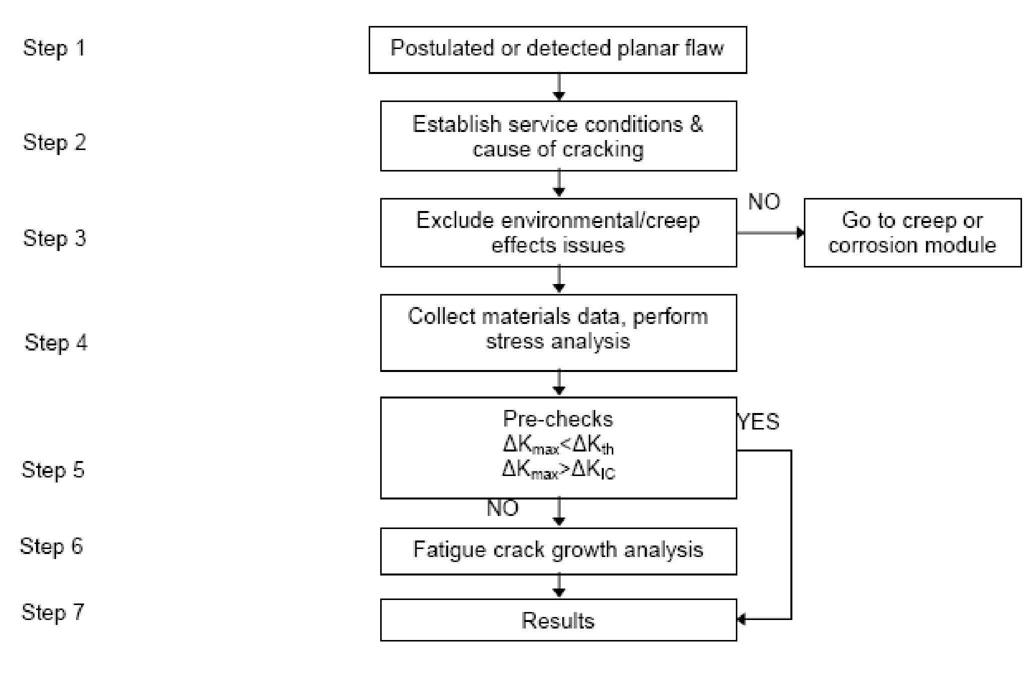
ASSESSMENT ROUTES

ROUTE 4 – Fatigue crack growth assessment

The basic steps of the procedure are shown in the flowchart in the figure:



Stepwise flowchart for Route 4

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ASSESSMENT ROUTES

ROUTE 4 – Fatigue crack growth assessment

Step 1: Detected or Postulated Planar Flaw.

The defect type, position and size should be identified.

Step 2: Establish Service Conditions and Cause of Cracking.

The service life to date and the desired future service life should be defined. The cause of the cracking should be established to ensure that the fatigue crack growth procedure is applicable.

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ASSESSMENT ROUTES

ROUTE 4 – Fatigue crack growth assessment

Step 3: Exclude Environmental or Creep Effects

If the flaw is characterised as surface breaking, the effects of the environment shall be considered on the fracture and fatigue properties. This requires it to be demonstrated that the environment in question does not influence these properties or that any effects are accounted for in the materials data used in the analysis.

If the temperature during operating in the vicinity of the flaw exceeds $0.4T_m$, where T_m is melting point of the material in ºK, time-dependent effects may need to be considered and the user is referred to the creep module (Section 8).

Step 4: Collect Materials Data and Perform Stress Analysis.

The materials relevant to the assessed feature including, in the case of weldments, the weld metal and heat-affected zone structures, shall be defined.

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ASSESSMENT ROUTES

ROUTE 4 – Fatigue crack growth assessment

Step 5: Pre-Checks Stability of the Flaw for the Maximum Foreseen Load (see 7.3.4.5)

Step 6: Calculate Crack Growth

The crack size at the end of the assessed period of operation is calculated by integrating the appropriate fatigue crack growth expression. This involves three sub-steps, which are repeated for pre-set cyclic increments:

•update the stress intensity factor as a function of the current flaw dimensions;

•compute the increment in crack size from the crack growth rate law;

•check its stability at fault or overload load levels using the fracture procedure.

The Procedure describes these for the Paris Law and Forman-Mettu approaches.(see Section 7.3.4.6)

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FATIGUE ASSESSMENT ROUTES

ROUTE 4 – Fatigue crack growth assessment

Paris Equation:

The relevant equation is as follows:

$$\frac{da}{dN} = A.\Delta K^{m}$$

where A and m are constants which depend on the material and the applied conditions, including environment and cyclic frequency.

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FATIGUE ASSESSMENT ROUTES

ROUTE 4 – Fatigue crack growth assessment

Forman-Mettu Approach:

This method follows a similar cycle-by-cycle integration method as discussed above using the sigmoidal crack growth rate relationship::

$$\frac{da}{dN} = C\left[((1-f)/(1-R))\cdot\Delta K\right]^n \frac{\left(1-\frac{\Delta K_{th}}{\Delta K}\right)^p}{\left(1-\frac{K_{max}}{K_c}\right)^q}$$

where N is the number of applied fatigue cycles, a is the crack length, and C, n, p, and q are empirically derived constants. For further information see Section 7.3.4.6.2.

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FATIGUE ASSESSMENT ROUTES

ROUTE 5 – Non-planar flaw assessment

Non-planar flaws can be assessed in the same way as planar flaws using route 4. Since they are not crack-like, this will be conservative. However, it may be the only option if it is necessary to quantify the growth of the flaw under fatigue loading and to ensure the margin against unstable fracture at a specific crack size.

Otherwise, Route 1 using S-N curves for welded joints can be applied directly, in cases for which the equivalent fatigue strength are established for the non-planar flaw under consideration. At present, this approach is only available for assessing slag inclusions or porosity in steel or aluminium alloy butt welds

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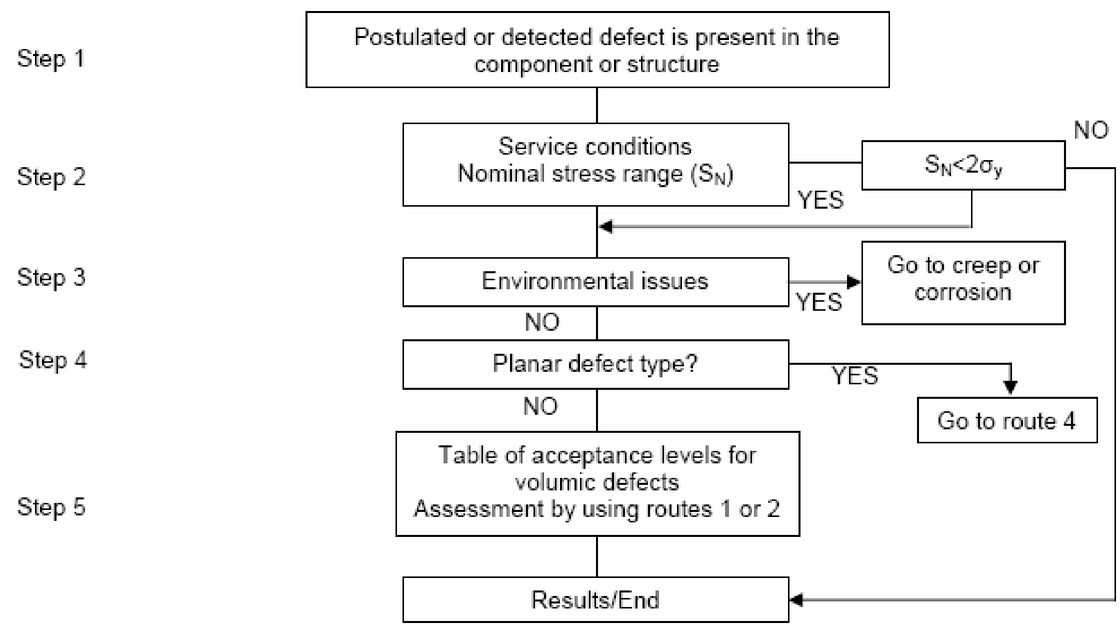
ASSESSMENT ROUTES

ROUTE 5 – Non-planar flaw assessment



Stepwise flowchart for Route 5

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ASSESSMENT ROUTES

ROUTE 5 – Non-planar flaw assessment

Step 1 Postulated or detected non planar defect is present in the component or structure

The route 5 assumed that a non planar defect is postulated or is detected by NDE in the structure or component which is assessed in fatigue.

Step 2 Service condition

Fatigue resistance will be calculated in route 5 by using nominal stress range S_N or Hot spot stress range calculation as defined in routes 1 and 2.

Step 3 Environmental issues (see 7.2.2)

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ASSESSMENT ROUTES

ROUTE 5 – Non-planar flaw assessment

Step 4 Types of imperfections

A -Imperfect shape : Undercut

B- Volumetric discontinuities

- Gas pores and cavities of any shape
- Solid inclusions such as isolated slag, slag lines, flux, oxides and metallic inclusions

C- Planar discontinuities

If a volumetric discontinuity is surface breaking or near the surface, or there is any doubt about the type of an embedded discontinuity, it shall be assessed like a planar discontinuity.

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ASSESSMENT ROUTES

ROUTE 5 – Non-planar flaw assessment

Step 5 Effects and assessment of imperfections

At geometrical imperfections, two effects affecting fatigue resistance can be distinguished:

1- *Nominal stress and Local notch effect* (Route 1)

2- *Crack like imperfection* (Route 4)

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SPECIAL OPTIONS

SPECIAL OPTIONS

FITNET Procedure provides guidance for the analysis of common industrial fatigue problems, such us the following:

- Dang Van criterion (see 7.5.1)
- Multi axial analysis (see 7.5.2)
- Rolling contact fatigue (see 7.5.3)
- Fatigue- creep (see 7.5.4)
- Fatigue- corrosion (see 7.5.5)
- Growth of Short crack (see 7.5.6)

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